Electronic Devices and Circuits

Fifth Edition

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Basic Semiconductor and *pn*-Junction Theory

Objectives

You will be able to:

1 Describe an atom, and sketch a diagram to show its components.
2 Explain energy levels and energy bands relating to electrons, and define valence band and conduction band.
3 Describe how electric current flow occurs by electron motion and by hole transfer.
4 Explain conventional current direction and direction of electron flow.
5 Sketch a diagram to show the relationship between covalently bonded atoms.
6 Discuss the differences between conductors, insulators, and semiconductors.
7 Explain how *n*-type and *p*-type semiconductor materials are created, and discuss the differences between the two types.
8 Sketch a *pn*-junction, and explain the origin of the junction depletion region.
9 Draw diagrams to show the effects of forward biasing and reverse biasing a *pn*-junction.
10 Sketch the current/voltage characteristics for forward-biased and reverse-biased *pn*-junctions.
11 Discuss temperature effects on conductors, insulators, semiconductors, and *pn*-junctions.
12 Calculate current and voltage levels at a *pn*-junction.

INTRODUCTION

An electronic device controls the movement of electrons. The study of electronic devices requires a basic understanding of the relationship between electrons and the other components of an atom. The movement of electrons within a solid and the bonding forces between atoms can then be investigated. This leads to a knowledge of the differences between conductors, insulators, and semiconductors, and to an understanding of *p*-type and *n*-type semiconductor material.

Junctions of *p*-type and *n*-type material (*pn*-junctions) are basic to all but a very few semiconductor devices. Forces act upon electrons that are adjacent to a *pn*-junction, and these forces are altered by the presence of an external bias voltage.

1-1 ATOMIC THEORY

The Atom

The atom can be thought of as consisting of a central *nucleus* surrounded by orbiting *electrons* (see Fig. 1-1). It may be compared to a planet with orbiting satellites. Just as satellites are held in orbit by the attractive force of gravity due to the mass of the planet, so each electron is held in orbit by an *electrostatic force of attraction* between it and the nucleus.

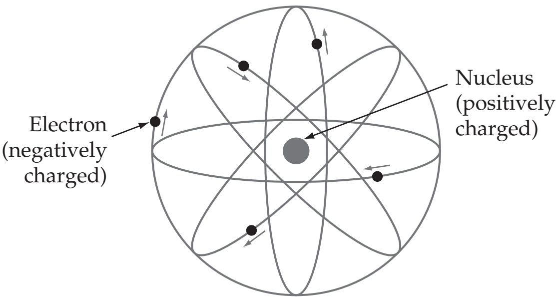


Figure 1-1 The atom consists of a central nucleus surrounded by orbiting electrons. The electrons have a negative charge, and the nucleus contains protons that are positively charged.

Each electron has a negative electrical charge of 1.602×10^{-19} Coulombs (C), and some particles within the nucleus have a positive charge of the same magnitude. Because opposite charges attract, a force of attraction exists between the oppositely charged electron and nucleus. Compared to the mass of the nucleus, electrons are relatively tiny particles of almost negligible mass. In fact, they can be considered to be little particles of negative electricity having no mass at all.

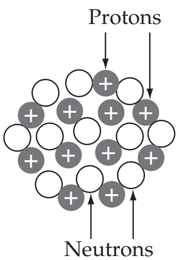


Figure 1-2 The nucleus of an atom is largely a cluster of protons and neutrons.

The nucleus of an atom (Fig. 1-2) is largely a cluster of two types of particles, *protons* and *neutrons*. Protons have a positive electrical charge, equal in magnitude (but opposite in polarity) to the negative charge on an electron. A neutron has no charge at all. Protons and neutrons each have masses about 1800 times the mass of an electron. For a given atom, the number of protons in the nucleus normally equals the number of orbiting electrons.

Because the protons and orbital electrons are equal in number and equal and opposite in charge,

they neutralize each other electrically. For this reason, all atoms are normally electrically neutral. If an atom loses an electron, it has lost some negative charge. Consequently, it becomes positively charged and is referred to as a *positive ion* (see Fig. 1-3a). Similarly, if an atom gains an additional electron, it becomes negatively charged and is termed a *negative ion* (Fig. 1-3b).

The differences between atoms consist largely of dissimilar numbers and arrangements of the three basic types of particle. However, all electrons are

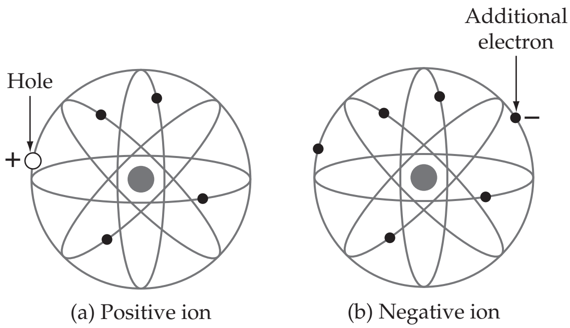


Figure 1-3 Positive and negative ions are created when an atom gains or loses an electron.

identical, as are all protons and all neutrons. An electron from one atom could replace an electron in any other atom. Different materials are made up of different types of atoms or different combinations of several types of atoms.

The number of protons in an atom is referred to as the *atomic number* of the atom. The *atomic weight* is approximately equal to the total number of protons and neutrons in the nucleus of the atom. The atom of the semiconductor material *silicon* has 14 protons and 14 neutrons in its nucleus, as well as 14 orbital electrons. Therefore, the atomic number for silicon is 14, and its atomic weight is approximately 28.

Electron Orbits and Energy Levels

Atoms may be conveniently represented by the two-dimensional diagrams shown in Fig. 1-4. It has been found that electrons can occupy only certain orbital rings or *shells* at fixed distances from the nucleus and that each shell can contain only a particular number of electrons. The electrons in the outer shell determine the electrical (and chemical) characteristics of each particular type of atom. These electrons are usually referred to as *valence electrons.* An atom may have its outer shell, or *valence shell,* completely filled or only partially filled.

The atoms represented in Fig. 1-4 are those of two important semiconductor materials, *silicon* (*Si*) and *germanium* (*Ge*). It is seen that each of these atoms has four electrons in a valence shell that can contain a maximum of eight. So, the valence shells have four electrons and four *holes.* A *hole* is

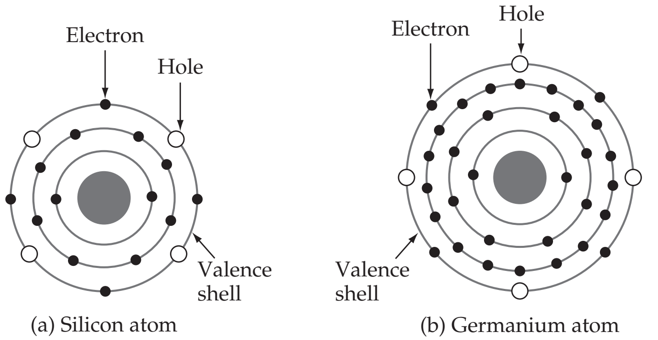


Figure 1-4 Two-dimensional representations of silicon and germanium atoms. The outer shells have four electrons and four holes.

defined as an absence of an electron in a shell where one could exist. Even though the valence shells of silicon and germanium have four holes, both types of atoms are electrically neutral because the total number of orbiting (negatively charged) electrons equals the total number of (positively charged) protons in the nucleus.

The closer an electron is to the nucleus, the stronger are the forces that bind it to the atom. Each shell has an *energy level* associated with it that represents the amount of energy required to extract an electron from the atom. Since the electrons in the valence shell are farthest from the nucleus, they require the least amount of energy to extract them (see Fig. 1-5a). Conversely, those electrons closest to the nucleus require the greatest energy application to extract them from the atom.

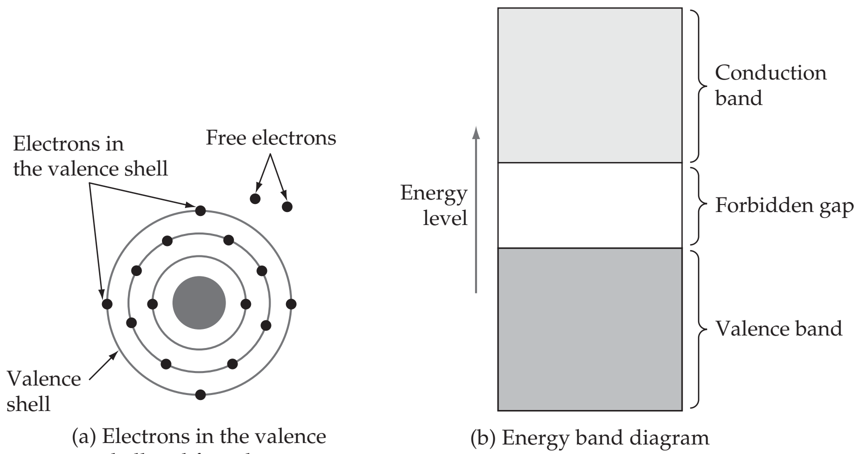


Figure 1-5 The energy level of electrons within a solid is shown by the energy band diagram. Electrons in orbit around a nucleus are in the valence band. Electrons which have broken away from an atom are in the conduction band.

The energy levels of the orbiting electrons are measured in *electron volts* (eV). An electron volt is defined as the amount of energy required to move one electron through a voltage difference of one volt.

Energy Bands

Up to this point the discussion has concerned a system of electrons in one isolated atom. The electrons of an isolated atom are acted upon only by the forces within that atom. However, when atoms are brought closer together, as in a solid, the electrons come under the influence of forces from other atoms. Under these circumstances, the energy levels that may be occupied by electrons merge into bands of energy levels. There are two distinct energy bands in which electrons may exist: the *valence band* and the *conduction band.* Separating these two bands is an *energy gap,* termed the *forbidden gap,* in which electrons cannot normally exist. The valence band, conduction band, and forbidden gap are shown diagrammatically in Fig. 1-5b.

Electrons in the conduction band of energy levels have become disconnected from atoms and are drifting around in the material. Conduction band electrons may be easily moved by the application of relatively small amounts of energy. Much larger amounts of energy must be applied to move an electron in the valence band of energy levels. Electrons in the valence band are usually in orbit around a nucleus. Depending upon the particular material, the forbidden gap may be large, small, or non-existent. The distinction between conductors, insulators, and semiconductors is largely concerned with the relative widths of the forbidden gap.

It is important to note that *the energy band diagram is simply a graphic representation of the energy levels associated with electrons.* To repeat, the electrons in the valence band are actually in orbit around the nucleus of an atom; those in the conduction band are drifting in the spaces between atoms.

Section 1-1 Review

1-1.1 Define nucleus, electron, electronic charge, proton, neutron, shell, positive ion, and negative ion.

1-1.2 What is meant by atomic number and atomic weight? State the atomic number and atomic weight for silicon.

1-1.3 Define conduction band, valence band, and forbidden gap.

1-2 CONDUCTION IN SOLIDS

Electron Motion and Hole Transfer

Conduction occurs in any material when an applied voltage causes electrons in the material to move in a particular direction. This may be due to one or both of

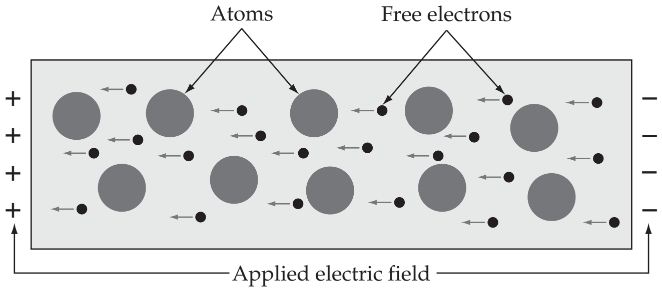


Figure 1-6 Free electrons are easily moved by an applied voltage to create an electric current.

two processes: *electron motion* and *hole transfer.* In electron motion, free electrons in the conduction band are moved under the influence of the applied electric field, thus creating an electric current (see Fig. 1-6). Since electrons have a negative charge, they are repelled from the negative terminal of the applied voltage and attracted toward the positive terminal. Hole transfer involves electrons which are still attached to atoms (those in the valence band).

If some of the electron positions in the valence shell of an atom are not occupied by electrons, there are holes where electrons could exist. When

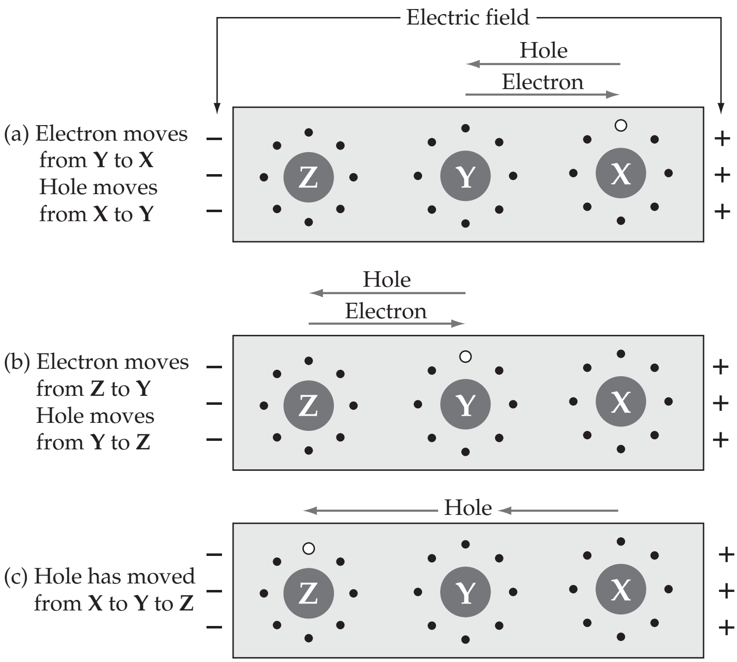


Figure 1-7 Conduction by hole transfer. An electron can be made to jump from one atom to another atom under the influence of an applied voltage. This causes the hole to move in the opposite direction.

sufficient energy is applied, an electron may be made to jump from one atom to a hole in another atom. When it jumps, the electron leaves a hole behind it, and consequently the hole has moved in a direction opposite to that of the electron.

Figure 1-7 illustrates a situation where there are no free electrons. However, those electrons in orbit around atoms experience a force of attraction to the positive terminal of the applied voltage, and repulsion from the negative terminal. This force can cause an electron to jump from one atom to another, moving toward the positive terminal.

Figure 1-7a shows an electron jumping from atom Y to atom X (toward the positive terminal of the applied voltage). When this occurs, the hole in the valence shell of atom X is filled, and a hole is left in the valence shell of atom Y (Fig. 1-7b). If an electron now jumps from atom Z to fill the hole in Y, a hole is left in the valence shell of Z (Fig. 1-7c). The hole has moved from atom X to atom Y to atom Z. A flow of current (electron motion) has occurred, and this may be said to be due to *hole movement*, or *hole transfer.*

Holes may be thought of as *positively charged particles*, and as such, they move through an electric field in a direction opposite to that of electrons. (Positive particles are attracted toward the negative terminal of an applied voltage.) In the circumstance illustrated in Fig. 1-7 where there are few free electrons, it is more convenient to think of hole movement than of electrons jumping from atom to atom.

Since the flow of electric current is constituted by the movement of electrons and holes, electrons and holes are referred to as *charge carriers.* Each time a hole moves, an electron must be supplied with enough energy to enable it to escape from its atom. Free electrons can be moved with less application of energy than holes because they are already disconnected from their atoms. For this reason, electrons have *greater mobility* than holes.

Conventional Current and Electron Flow

In the early years of electrical experimentation it was believed that a positive charge represented an increased amount of electricity and that a negative charge was a reduced quantity. Consequently, current was assumed to flow from positive to negative. This is a convention that remains in use today even though current is now known to be a movement of electrons from negative to positive (see Fig. 1-8).

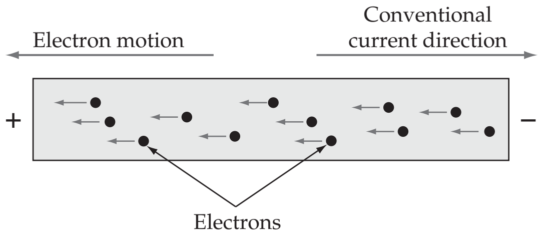


Figure 1-8 Conventional current direction is from positive to negative. Electron flow is from negative to positive.

Current flow from positive to negative is referred to as the conventional current direction.

Electron flow from negative to positive is known as the direction of electron flow.

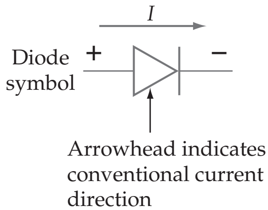


Figure 1-9 All graphic symbols for electronic devices have arrowheads that indicate conventional current direction.

It is important to understand both electron flow and conventional current direction. The operation of electronic devices is explained in terms of electron movement. However, *every graphic symbol used to represent an electronic device has an arrowhead which indicates conventional current direction* (see the diode symbol in Fig. 1-9). Consequently, electronic circuits are most easily explained by using current flow from positive to negative.

Section 1-2 Review

1-2.1 Draw sketches to show the process of current flow by electron motion and by hole transfer.

1-2.2 Explain the difference between conventional current direction and direction of electron flow.

1-3 CONDUCTORS, SEMICONDUCTORS, AND INSULATORS

Bonding Forces between Atoms

Whether a material is a conductor, a semiconductor, or an insulator depends largely upon what happens to the outer-shell electrons when the atoms bond themselves together to form a solid. In the case of copper, the easily detached valence electrons are given up by the atoms. As illustrated in Fig. 1-10, this creates a great mass of free electrons (or *electron gas*) drifting about in the space between the copper atoms. The electrons are easily moved under the influence of an applied voltage to create a current flow. The bonding force that holds atoms together in a conductor is known as *metallic bonding.*

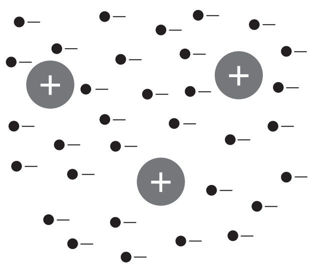


Figure 1-10 In metallic bonding a mass of free electrons is drifting around in the space between atoms.

Semiconductor atoms normally have four outer-shell electrons and four holes, and they are so close together that the outer-shell

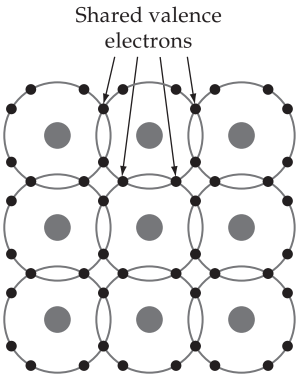


Figure 1-11 Covalent bonding in semiconductors produces very few free electrons or holes for current flow.

electrons behave as if they were orbiting in the valence shells of two atoms. In this way each valence-shell electron fills one of the holes in the valence shell of an adjacent atom. This produces a bonding force referred to as *covalent bonding*. As shown in Fig. 1-11, it would appear that there are no holes and no free electrons drifting about in the semiconductor material. In fact, some of the electrons are so weakly attached to their atoms that they can be made to break away to create a current flow when a voltage is applied.

In some insulating materials the atoms bond together in a similar way to semiconductor atoms (*covalent bonding*). But the valence-shell electrons are so strongly attached to the atoms in an insulator that no charge carriers are available for current flow. In other types of insulating materials, some atoms give up outer-shell electrons, which are accepted into the orbit of nearby atoms. Because the atoms are *ionized*, this is termed *ionic bonding* (see Fig. 1-12). Here again, all of the electrons are very strongly attached to atoms, and the possibility of current flow is virtually zero.

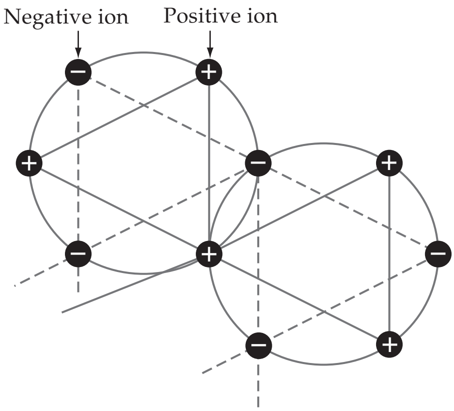


Figure 1-12 Ionic bonding occurs in some insulating materials. There are no holes or free electrons to facilitate current flow.

Energy Bands in Different Materials

The energy band diagrams in Fig. 1-13 show that insulators have a wide forbidden gap, semiconductors have a narrow forbidden gap, and conductors have no forbidden gap at all.

In the case of insulators, there are practically no electrons in the conduction band, and the valence band is filled. Moreover, the forbidden gap is so wide (Fig. 1-13a) that it would require the application of relatively large amounts of energy to cause an electron to cross from the valence band to the conduction band. Therefore, when a voltage is applied to an insulator, conduction cannot normally take place either by electron motion or hole transfer.

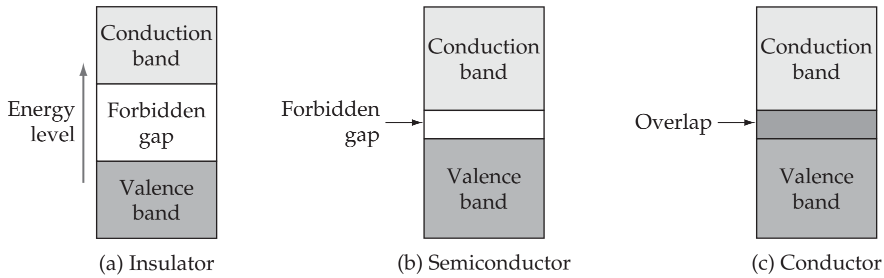


Figure 1-13 Energy band diagrams for insulators, semiconductors, and conductors.

For semiconductors at a temperature of absolute zero (−273°C), the valence band is usually full and there may be no electrons in the conduction band. As shown in Fig. 1-13b, the forbidden gap in a semiconductor is very much narrower than that in an insulator, and the application of small amounts of energy can raise electrons from the valence band to the conduction band. Sufficient thermal energy for this purpose is available when the semiconductor is at normal room temperature. If a voltage is applied to the semiconductor, conduction can occur by both electron movement in the conduction band and by hole transfer in the valence band.

In the case of a conductor (Fig. 1-13c) there is no forbidden gap, and the valence and conduction energy bands overlap. For this reason, very large numbers of electrons are available for conduction, even at extremely low temperatures.

Typical resistance values for a one-centimetre-cube sample are the following: conductor $10^{-6}\ \Omega$; semiconductor $10\ \Omega$; insulator $10^{14}\ \Omega$.

Section 1-3 Review

1-3.1 Briefly describe the type of atomic bonding that occurs in (a) insulators and (b) conductors.

1-3.2 Draw a sketch to show the bonding of atoms in semiconductor material. Briefly explain.

1-3.3 Sketch and explain the energy band diagrams for conductors, insulators, and semiconductors.

1-4 *n*-TYPE AND *p*-TYPE SEMICONDUCTORS

Doping

Pure semiconductor material is known as *intrinsic* material. Before intrinsic material can be used in the manufacture of a device, *impurity atoms* must be added to improve its conductivity. The process of adding the atoms is termed *doping.* Two different types of doping are possible: *donor doping* and *acceptor doping*. Donor doping generates free electrons in the conduction band (that is, electrons that are not tied to an atom). Acceptor doping produces valence-

band holes, or a shortage of valence electrons in the material. After doping, the semiconductor material is known as *extrinsic* material.

n-Type Material

In donor doping, illustrated in Fig. 1-14, impurity atoms that have five electrons and three holes in their valence shells are added to the undoped material. The impurity atoms form covalent bonds with the silicon or germanium atoms. Because the semiconductor atoms have only four electrons and four holes in their valence shells, there is one extra valence-shell electron for each impurity atom added. Each additional electron produced in this way enters the conduction band as a free electron. Because the free electrons have *negative charges,* donor-doped semiconductor is known as *n-type material.*

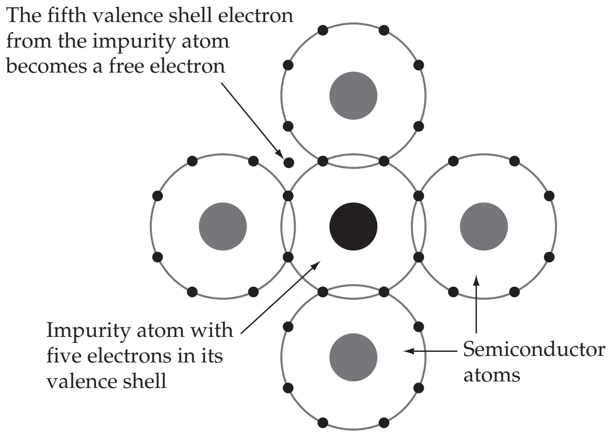


Figure 1-14 **In donor doping, impurity atoms with five valence-shell electrons and three holes are added to the semiconductor material.**

Free electrons in the conduction band are easily moved around under the influence of an electric field. Consequently, conduction takes place largely by electron motion in donor-doped semiconductor material. The doped material remains electrically neutral (neither positively charged nor negatively charged) because the total number of electrons (including the free electrons) is still equal to the total number of protons in the atomic nuclei.

The term *donor doping* comes from the fact that an electron is *donated* to the conduction band by each impurity atom. Typical donor materials are *antimony, phosphorus,* and *arsenic.* Since these atoms each have five valence electrons, they are referred to as *pentavalent atoms.*

p-Type Material

The impurity atoms used for acceptor doping (see Fig. 1-15) have outer shells containing three electrons and five holes. Suitable atoms with three valence

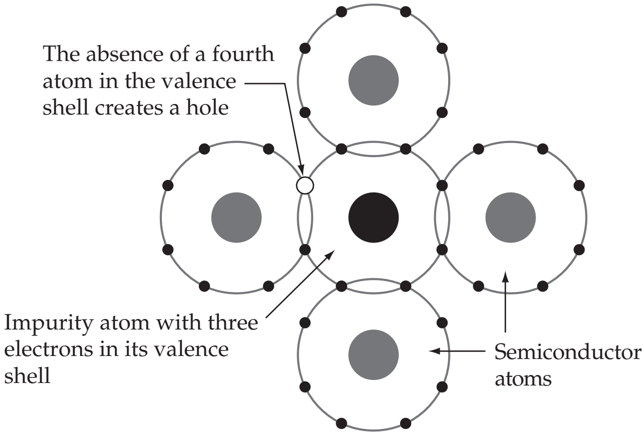


Figure 1-15 Acceptor doping requires the use of impurity atoms that have three electrons and five holes in the valence shells. This creates holes in the semiconductor material.

electrons (*trivalent atoms*) are *boron, aluminum,* and *gallium.* These atoms form covalent bonds with the semiconductor atoms, but the bonds lack one electron for a complete outer shell of eight. In Fig. 1-15 the impurity atom illustrated has only three valence electrons; so a hole exists in its bond with the surrounding atoms. It is seen that in acceptor doping, holes are introduced into the valence band so that conduction may occur by the process of hole transfer.

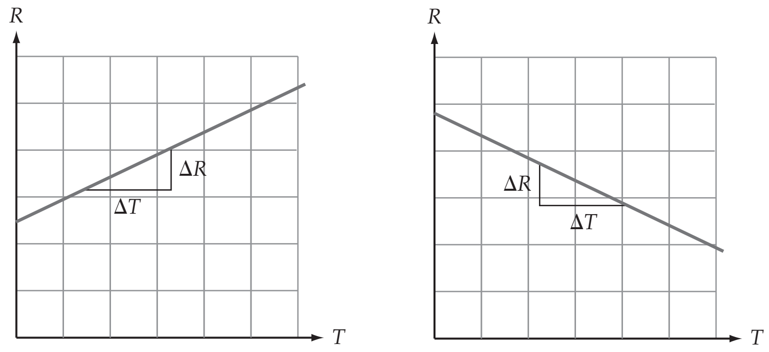
Since holes can be said to have a *positive charge,* acceptor-doped semiconductor material is referred to as *p-type material.* Like the *n*-type, *p*-type material remains electrically neutral, because the total number of orbital electrons in each impurity atom is equal to the total number of protons in its atomic nucleus. The term *acceptor doping* comes from the fact that holes can *accept* a free electron.

Majority and Minority Charge Carriers

In undoped semiconductor material at room temperature there are a number of free electrons and holes. That is because thermal energy causes some electrons to break the bonds with their atoms and enter the conduction band. This process, which creates pairs of holes and electrons, is appropriately termed *hole-electron pair generation.* The opposite effect, called *recombination,* occurs when an electron *falls into* a hole in the valence band. Because there are many more electrons than holes in *n*-type material, electrons are referred to as the *majority charge carriers,* and holes as the *minority carriers* in *n*-type material. In *p*-type material, holes are the majority carriers and electrons are minority carriers.

Effects of Heat and Light

When a conductor is heated, the atoms (which are in fixed locations) tend to vibrate, and the vibration impedes the movement of the surrounding mass of electrons (see Fig. 1-10). This causes a reduction in the flow of the electrons that constitute the electric current. The reduced current flow means that the conductor's resistance has increased. So a conductor has a *positive temperature coefficient* (*PTC*) of resistance, a resistance that increases with increasing temperature. This is illustrated in Fig. 1-16a.



(a) A conductor has a positive temperature coefficient

(b) A semiconductor has a negative temperature coefficient

Figure 1-16 The resistances of conductors and semiconductors are affected differently by temperature change.

When undoped semiconductor material is at a temperature of absolute zero (−273°C), all electrons are in normal orbit around the atoms and there are virtually no free electrons in the conduction band and no holes in the valence band. Consequently, at −273°C a semiconductor behaves as an insulator.

When the temperature of the semiconductor is raised, electrons break away from their atoms and move from the valence band to the conduction band. This produces holes in the valence band and free electrons in the conduction band, allowing conduction to occur by electron movement and by hole transfer. Increasing the application of thermal energy generates an increasing number of hole-electron pairs.

As in the case of a conductor, thermal vibration of atoms occurs in a semiconductor. However, there are very few electrons to be impeded in a semiconductor compared to the large numbers in a conductor. The thermal generation of electrons is the dominating factor, and the semiconductor current increases as the temperature rises. This represents a decrease in resistance with rising temperature, or a *negative temperature coefficient* (*NTC*) (Fig. 1-16b). Heavily doped semiconductor material is an exception in that it behaves more like a conductor than a semiconductor.

Just as thermal energy can cause electrons to break their atomic bonds, so hole-electron pairs can be generated by energy applied to a semiconductor in the form of light. A material that has few free electrons available for conduction when not illuminated is said to have a high *dark resistance.* When the semiconductor material is illuminated, its resistance decreases and may become comparable to that of a conductor.

Charge Carrier Density

Table 1-1 lists some typical quantities for intrinsic silicon and germanium at a temperature of 300 K (which is equivalent to 27°C). The number of atoms per cubic centimetre is 5×10^{22}, and the electron density (the number of free electrons per cubic centimetre) is $n_i = 1.5 \times 10^{10}/\text{cm}^3$. This means that 1.5×10^{10} atoms have each released one electron (due to thermal energy at 27°C), and consequently, 1.5×10^{10} holes have been created. So the hole density (p_i) is the same as the electron density (n_i) in intrinsic semiconductor,

$$p_i = n_i \tag{1-1}$$

Table 1-1 Typical Quantities for Intrinsic Silicon and Germanium at 300 K

	Silicon	Germanium
Atomic density (per cm^3)	5×10^{22}	4.4×10^{22}
Electron density (n_i) (per cm^3)	1.5×10^{10}	2.5×10^{13}
Electron mobility (μ_n) (cm^2/V.s)	1500	3800
Hole mobility (μ_p) (cm^2/V.s)	500	1800

If an *n*-type material has a density of *n* free electrons per cubic centimetre, some of the electrons will drop into holes, so that the intrinsic hole density (p_i) is reduced. Similarly, for *p*-type with a density of *p* holes, some free electrons are absorbed into holes, causing a reduction in the intrinsic free electron density (n_i). It can be demonstrated that the hole-electron density product for extrinsic material equals that for intrinsic material. This is termed as the *mass action law*,

$$pn = p_i\, n_i \tag{1-2}$$

Also, in intrinsic material $p_i = n_i$, so that

$$pn = n_i^2 \tag{1-3}$$

When an intrinsic material is doped with N_D donor atoms per cubic centimetre, each donor atom releases an electron, so that the atom becomes a

positive ion. This adds to the positive charges from the hole density (p), so that the total positive charge density is

$$N_D + p$$

As the total negative and positive charges are equal, the electron density is

$$\boxed{n = N_D + p} \tag{1-4}$$

Similarly, when the material is doped with N_A acceptor atoms per cubic centimetre, each acceptor atom absorbs a free electron and becomes a negative ion. This adds to the negative charges from the free electron density (n), so that the total negative charge density is $N_A + n$ and because the total negative and positive charges are equal, the hole density is

$$\boxed{p = N_A + n} \tag{1-5}$$

When both donor and acceptor doping are involved,

$$\boxed{N_D + p = N_A + n} \tag{1-6}$$

Example 1-1

A block of silicon is doped with a donor atom density of $N_D = 3 \times 10^{14}$ atoms/cm^3, and with an acceptor atom density of $N_A = 0.5 \times 10^{14}$ atoms/cm^3. Determine the resultant densities of free electrons and holes.

Solution

From Eq. 1-6, $\quad n = N_D - N_A + p$

From Eq. 1-3, $\quad p = n_i^2/n$

so, $\quad n = N_D - N_A + (n_i^2/n)$

giving $\quad n^2 + (N_A - N_D)\, n - n_i^2 = 0$

Using the quadratic equation formula to solve for n

$$n = \{-(N_A - N_D) + \sqrt{(N_A - N_D)^2 + 4n_i^2}\}/2$$

$$= \{(-2.5 \times 10^{14}) + \sqrt{(-2.5 \times 10^{14})^2 + 4(1.5 \times 10^{10})^2}\}/2$$

$$= 2.5 \times 10^{14} \text{ electrons/cm}^3$$

Alternatively, because $N_D >> N_A$, $n >> p$

From Eq. 1-6, $n \approx N_D - N_A = 3 \times 10^{14} - 0.5 \times 10^{14}$

$= 2.5 \times 10^{14}$

and, from Eq. 1-3, $p = n_i^2/n = (1.5 \times 10^{10})^2/(2.5 \times 10^{14})$

$= 0.9 \times 10^6$ holes/cm^3

Section 1-4 Review

1-4.1 Draw a sketch to illustrate donor doping.

1-4.2 Draw a sketch to illustrate acceptor doping.

1-4.3 Define *n*-type material, *p*-type material, minority charge carriers, majority charge carriers, positive temperature coefficient, negative temperature coefficient, and dark resistance.

Practice Problems

1-4.1 Determine the number of free electrons and holes in a sample of silicon which is doped with 4×10^{14} donor atoms/cm^3 and 3.3×10^{14} acceptor atoms/cm^3.

1-4.2 Repeat Problem 1-4.1 for a germanium sample if the electron density in intrinsic germanium is 2.5×10^{13}.

1-5 SEMICONDUCTOR CONDUCTIVITY

Drift Current

In free space, an electric field will accelerate electrons in a straight line from the negative terminal to the positive terminal of the applied voltage. In a conductor or semiconductor at 25°C, a free electron under the influence of an electric field will move toward the positive terminal of the applied voltage, but will continually collide with atoms along the way. The situation is illustrated in Fig. 1-17. Each time the electron strikes an atom, it rebounds in a random direction. The presence of the electric field does not stop the collisions and random motion, but it does cause the electrons to drift in the direction of the positive terminal. Consequently, current produced in this way is termed as *drift current*, and it is the usual kind of current flow that occurs in conductors and semiconductors.

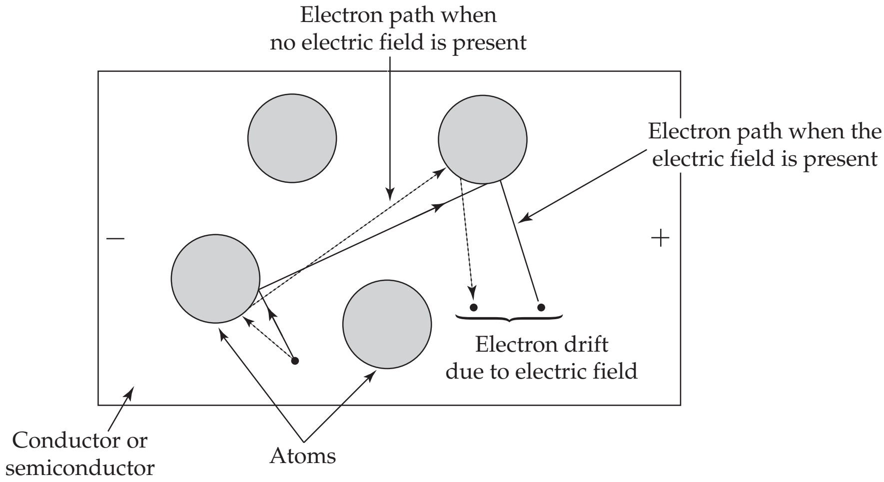


Figure 1-17 Drift current is the type of current flow that occurs in conductors and semiconductors when a voltage is applied. Electrons cannot travel in a straight line, but instead drift along, bouncing from one atom to another.

Diffusion Current

Figure 1-18 illustrates another type of current that occurs in semiconductors. Suppose a concentration of one type of charge carriers appears at one end of a piece of semiconductor material, as the result of a charge carrier injection from an external source. Because the charge carriers are either all electrons or all holes they have the same polarity, and thus there is a force of repulsion between them. This produces a tendency for the electrons to move gradually, or *diffuse,* away from the locality of high concentration toward one of low concentration until they are eventually distributed throughout the material. The movement of charge carriers constitutes an electric current, and so this type of current is known as a *diffusion current.*

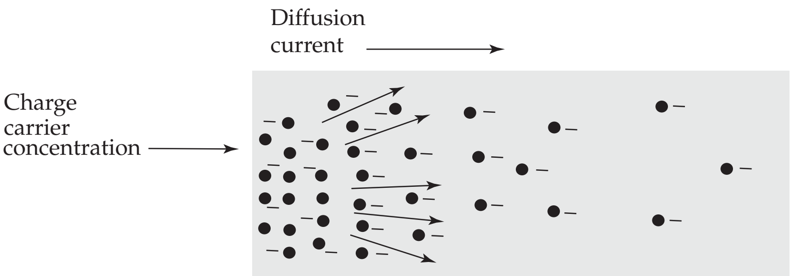


Figure 1-18 Diffusion current occurs when charge carriers diffuse from a point of concentration to spread uniformly throughout the material.

Charge Carrier Velocity

Recall from Section 1-2 that electrons have greater mobility than holes. The *mobility constants* (see Table 1-1) determine the electron and hole (drift

current) velocities under the influence of an electric field. For electron velocity (v_n) and hole velocity (v_p)

$$v_n = -\mu_n \mathscr{E} \tag{1-7}$$

and

$$v_p = \mu_p \mathscr{E} \tag{1-8}$$

where μ_n and μ_p are the electron and hole mobility constants, and $\mathscr{E}$ is the electric field strength. The minus sign in Eq. 1-7 indicates that the electrons move from negative to positive, opposite to conventional current direction.

Example 1-2

Calculate the drift current velocity for electrons and for holes in a 1 mm length of silicon at 27°C when the terminal voltage is 10 V.

Solution

Eq. 1-7: $$v_n = -\mu_n E/l = -1500\ \text{cm}^2 \times 10\ \text{V}/1\ \text{mm}$$

$$= -1500\ \text{m/s}$$

Eq. 1-8: $$v_p = \mu_p E/l = 500\ \text{cm}^2 \times 10\ \text{V}/1\ \text{mm}$$

$$= 500\ \text{m/s}$$

Conductivity

Recall from basic electrical studies that the resistance of a conductor is given by the equation

$$R = \rho l/a \tag{1-9}$$

where ρ is the *resistivity* of the material (in Ω.m), l is the length, and a is the cross-sectional area. This can be rewritten as

$$R = l/(\sigma a) \tag{1-10}$$

where σ is the material *conductivity* (the reciprocal of resistivity) $(\Omega.\text{m})^{-1}$.

For doped semiconductor having n free electrons and p holes, the conductivity is given by

$$\sigma = q(n\mu_n + p\mu_p) \tag{1-11}$$

where q is the electronic charge (1.602×10^{-19} C).

Example 1-3

A cylindrically shaped section of n-type silicon has a 1 mm length and 0.1 mm^2 cross-sectional area. Calculate its conductivity and resistance (a) when it is purely intrinsic material, and (b) when it has a free electron density of $n = 8 \times 10^{13}/\text{cm}^3$.

Solution

$l = 1$ mm $= 0.1$ cm and $a = 0.1$ mm^2 $= 10^{-3}$ cm^2

(a) From Table 1-1, the electron and hole density for intrinsic silicon is

$$n_\text{i} = 1.5 \times 10^{10}/\text{cm}^3$$

and the mobility constants are

$$\mu_\text{n} = 1500\ \text{cm}^2/\text{V.s} \quad \text{and} \quad \mu_\text{p} = 500\ \text{cm}^2/\text{V.s}$$

Eq. 1-11:
$$\sigma = q(n\mu_\text{n} + p\mu_\text{p})$$
$$= (1.6 \times 10^{-19})[(1.5 \times 10^{10} \times 1500) + (1.5 \times 10^{10} \times 500)]$$
$$= 4.8 \times 10^{-6}\ (\Omega.\text{cm})^{-1}$$

From Eq. 1-10, $R = l/(\sigma\ a) = 0.1/(4.8 \times 10^{-6}\ (\Omega.\text{cm})^{-1} \times 10^{-3}\ \text{cm}^2)$

$$= 20.8\ \text{M}\Omega$$

(b) For doped material

Eq. 1-3:
$$p = n_\text{i}^2/n = (1.5 \times 10^{10})^2/(8 \times 10^{13})$$
$$= 2.8 \times 10^6$$

Eq. 1-11:
$$\sigma = q(n\mu_\text{n} + p\mu_\text{p})$$
$$= (1.6 \times 10^{-19})[(8 \times 10^{13} \times 1500) + (2.8 \times 10^6 \times 500)]$$
$$= 0.019\ (\Omega.\text{cm})^{-1}$$

From Eq. 1-10, $R = l/(\sigma\, a) = 0.1\ \text{cm}/(0.019\ \Omega/\text{cm} \times 10^{-3}\ \text{cm}^2)$

$$= 5.26\ \text{k}\Omega$$

Section 1-5 Review

1-5.1 Draw diagrams to illustrate drift current and diffusion current, and briefly explain each type of current.

Practice Problems

1-5.1 Calculate the free electron density in a 1 mm cube of *n*-type silicon if its measured resistance is 35 kΩ.

1-5.2 Determine the applied voltage required to produce a drift current velocity of 1.2×10^5 cm/s in a 0.15 mm section of germanium.

1-5.3 Calculate the resistivity of intrinsic germanium at 27°C.

1-6 THE *pn*-JUNCTION

Junction of *p*-Type and *n*-Type

Two blocks of semiconductor material are represented in Fig. 1-19: one block is *p*-type material, and the other is *n*-type. The small circles in the *p*-type material represent holes, which are the majority charge carriers in *p*-type. The dots in the *n*-type material represent the majority charge carrier free electrons within that material. Normally, the holes are uniformly distributed throughout the volume of the *p*-type semiconductor and the electrons are uniformly distributed in the *n*-type.

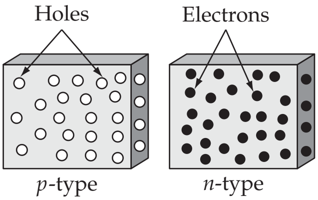


Figure 1-19 *p*-type and *n*-type semiconductor materials.

In Fig. 1-20, *p*-type and *n*-type semiconductor materials are shown side by side, representing a *pn-junction.* Since holes and

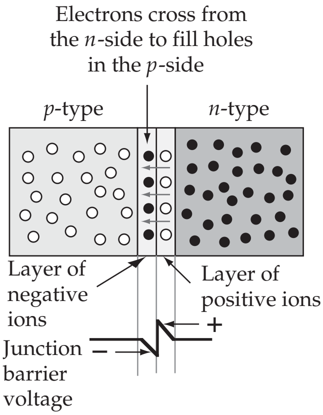


Figure 1-20 At a *pn*-junction, electrons cross from the *n*-side to fill holes in a layer on the *p*-side close to the junction.

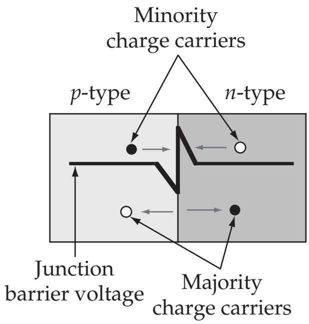


Figure 1-21 The barrier voltage at a *pn*-junction assists the flow of minority charge carriers and opposes the flow of majority charge carriers.

electrons are close together at the junction, some free electrons from the *n*-side are attracted across the junction to fill adjacent holes on the *p*-side. They are said to *diffuse* across the junction from a region of high carrier concentration to one of low concentration. The free electrons crossing the junction create negative ions on the *p*-side by giving some atoms one more electron than their total number of protons. The electrons also leave positive ions (atoms with one fewer electron than the number of protons) behind them on the *n*-side.

Barrier Voltage

The *n*-type and *p*-type materials are both electrically neutral before the charge carriers diffuse across the junction. When negative ions are created on the *p*-side, the portion of the *p*-side close to the junction acquires a negative voltage (Fig. 1-20). Similarly, the positive ions created on the *n*-side give the *n*-side a positive voltage close to the junction. The negative voltage on the *p*-side tends to repel additional electrons crossing from the *n*-side. Also (thinking of the holes as positive particles), the positive voltage on the *n*-side tends to repel any movement of holes from the *p*-side. So, the initial diffusion of charge carriers creates a *barrier voltage* at the junction, which is negative on the *p*-side and positive on the *n*-side. The transfer of charge carriers and the resultant creation of the barrier voltage occur when the *pn*-junctions are formed during the manufacturing process (see Chapter 7).

The magnitude of the barrier voltage at a *pn*-junction can be calculated from a knowledge of the doping densities, electronic charge, and junction temperature. Typical barrier voltages at 25°C are 0.3 V for germanium junctions and 0.7 V for silicon.

It has been explained that the barrier voltage at the junction opposes both the flow of electrons from the *n*-side and the flow of holes from the *p*-side. Because electrons are the majority charge carriers in the *n*-type material, and holes are the majority charge carriers in the *p*-type, it is seen that *the barrier voltage opposes the flow of majority carriers* across the *pn*-junction (see Fig. 1-21). Any free electrons generated by thermal energy on the *p*-side of the junction are attracted across the positive barrier to the *n*-side. Similarly, thermally generated holes on the *n*-side are attracted to the *p*-side through the negative barrier presented to them at the junction. Electrons on the *p*-side and holes on the *n*-side are minority charge carriers. Therefore, *the barrier voltage assists the flow of minority carriers across the junction* (Fig. 1-21).

Depletion Region

The movement of charge carriers across the junction leaves a layer on each side that is depleted of charge carriers. This is the *depletion region* shown in Fig. 1-22a. On the *n*-side, the depletion region consists of donor impurity atoms that, having lost the free electron associated with them, have become

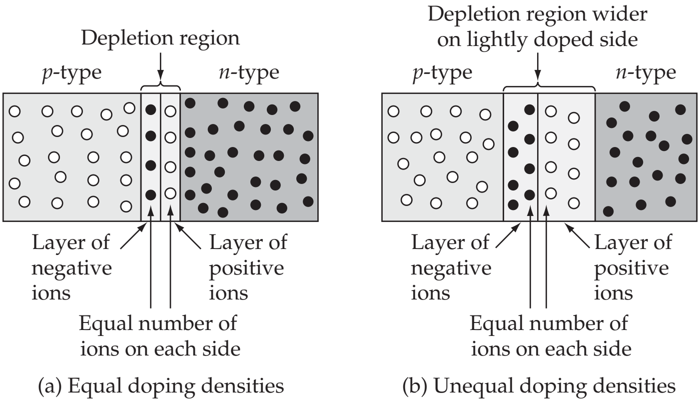


Figure 1-22 Charge carrier diffusion across a *pn*-junction creates a region that is depleted of charge carriers and that penetrates deepest into the more lightly doped side.

positively charged. The depletion region on the *p*-side is made up of acceptor impurity atoms that have become negatively charged by losing the hole associated with them. (The hole has been filled by an electron.)

On each side of the junction, equal numbers of impurity atoms are involved in the depletion region. If the two blocks of semiconductor material have equal doping densities, the depletion layers on each side have equal widths (Fig. 1-22a). If the *p*-side is more heavily doped than the *n*-side, as illustrated in Fig. 1-22b, the depletion region penetrates more deeply into the *n*-side in order to include an equal number of impurity atoms on each side of the junction. Conversely, when the *n*-side is more heavily doped, the depletion region penetrates deeper into the *p*-type material.

Summary

- A region depleted of charge carriers spreads across both sides of a *pn*-junction, penetrating farther into the less doped side.
- The depletion region contains an equal number of ionized atoms on opposite sides of the junction.
- A barrier voltage is created by the charge carrier depletion effect, positive on the *n*-side and negative on the *p*-side.
- The barrier voltage opposes majority charge carrier flow and assists the flow of minority charge carriers across the junction.

Section 1-6 Review

1-6.1 Sketch a *pn*-junction showing the depletion region. Briefly explain how the depletion region is created.

1-6.2 Explain the origin of the barrier voltage at a *pn*-junction. Discuss the effect of the barrier voltage on minority and majority charge carriers.

1-7 BIASED JUNCTIONS

Reverse-Biased Junction

When an external bias voltage is applied to a *pn*-junction, positive to the *n*-side and negative to the *p*-side, electrons from the *n*-side are attracted to the positive terminal, and holes from the *p*-side are attracted to the negative terminal. As shown in Fig. 1-23, holes on the *p*-side of the junction are attracted away from the junction and electrons are attracted away from the junction on the *n*-side. This causes the depletion region to be widened and the barrier voltage to be increased, as illustrated. With the barrier voltage increase, there is no possibility of a majority charge carrier current flow across the junction, and the junction is said to be *reverse biased.* Because there is only a very small reverse current, a reverse-biased *pn*-junction can be said to have a high resistance.

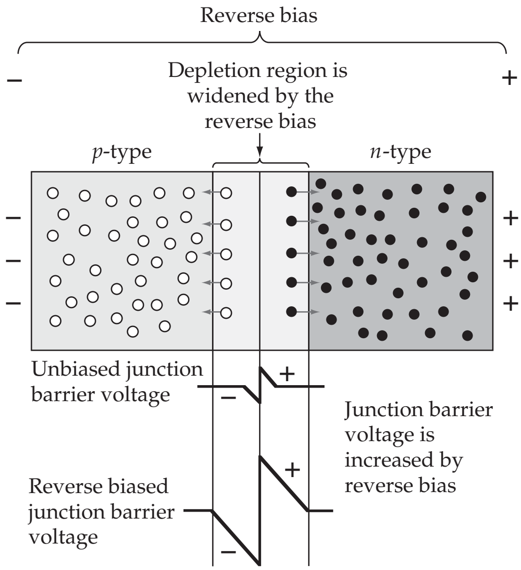


Figure 1-23 A reverse bias applied to a *pn*-junction (positive on the *n*-side, negative on the *p*-side) causes the depletion region to widen and increases the barrier voltage. Only a very small reverse current flows across the junction.

Although there is no possibility that a majority charge carrier current can flow across a reverse-biased junction, minority carriers generated on each side can still cross the junction. Electrons in the *p*-side are attracted across the junction to the positive voltage on the *n*-side. Holes on the *n*-side may flow across to the negative voltage on the *p*-side. This is shown by the junction reverse characteristic, or the graph of reverse current (I_R) versus reverse voltage (V_R) (Fig. 1-24). Since only a very small reverse-bias voltage is necessary to direct all available minority carriers across the junction, further increases in bias voltage do not increase the current level. This current is referred to as a *reverse saturation current.*

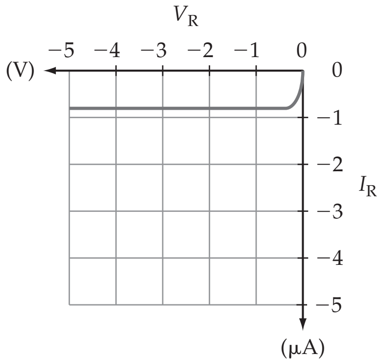


Figure 1-24 Current-versus-voltage characteristic for a reverse-biased *pn*-junction.

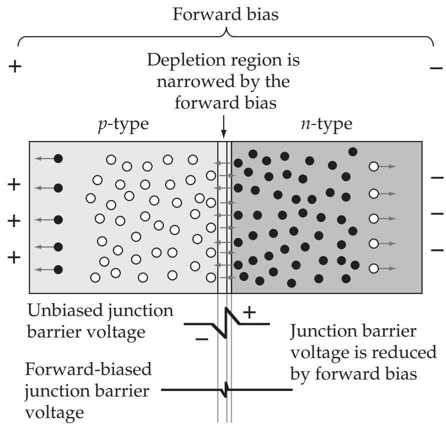


Figure 1-25 Forward biasing a *pn*-junction (positive on the *p*-side, negative on the *n*-side) narrows the depletion region, reduces the barrier voltage, and causes a relatively large current to flow across the junction.

The reverse saturation current is normally a very small quantity, ranging from nanoamps to microamps, depending on the junction area, temperature, and semiconductor material.

Forward-Biased Junction

Consider the effect of an external bias voltage applied with the polarity shown in Fig. 1-25: positive on the *p*-side and negative on the *n*-side. The holes on the *p*-side, being positively charged particles, are repelled from the positive terminal and driven toward the junction. Similarly, the electrons on the *n*-side are repelled from the negative terminal toward the junction. The result is that the width of the depletion region and the barrier potential are both reduced.

When the applied bias voltage is progressively increased from zero, the barrier voltage gets smaller until it effectively disappears and charge carriers easily flow across the junction. Electrons from the *n*-side are now attracted across to the positive bias terminal on the *p*-side, and holes from the *p*-side

flow across to the negative terminal on the *n*-side (thinking of holes as positively charged particles). A majority carrier current flows, and the junction is said to be *forward biased.*

The graph in Fig. 1-26 shows the forward current (I_F) plotted against forward voltage (V_F) for typical germanium and silicon *pn*-junctions. In each case, the graph is known as the *forward characteristic* of the junction. It is seen that there is very little forward current until V_F exceeds the junction barrier voltage (0.3 V for germanium, 0.7 V for silicon). When V_F is increased from zero toward the knee of the characteristic, the barrier voltage is progressively overcome, allowing more majority charge carriers to flow across the junction. Above the knee of the characteristic, I_F increases almost linearly with increase in V_F. The level of current that can be made to flow across a forward-biased *pn*-junction largely depends on the area of the junction.

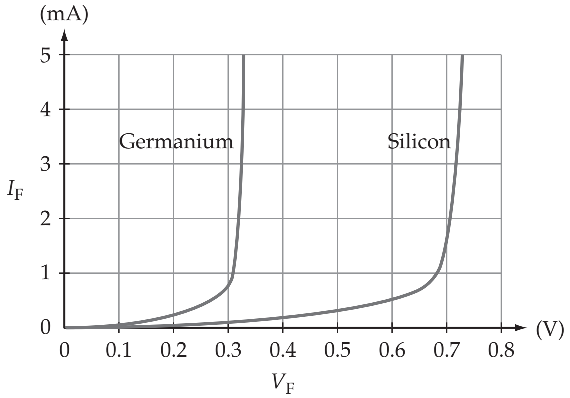


Figure 1-26 *pn*-junction forward characteristics. Germanium junctions are forward biased at approximately 0.3 V. A silicon junction requires approximately 0.7 V for forward bias.

Junction Temperature Effects

As already discussed, the reverse saturation current (I_o) at a *pn*-junction consists of minority charge carriers. When the temperature of the semiconductor material is raised, increasing numbers of electrons break away from their atoms. This generates additional minority charge carriers, causing I_o to increase as the junction temperature rises. When I_o is known for a given temperature (T_1), it can be calculated for another temperature level (T_2) from the following equation:

$$I_{o(T2)} \approx I_{o(T1)} (2^{T2-T1/10}) \qquad \textbf{(1-12)}$$

Example 1-4 demonstrates that I_o approximately doubles for each 10°C rise in temperature (Fig. 1-27a).

Example 1-4

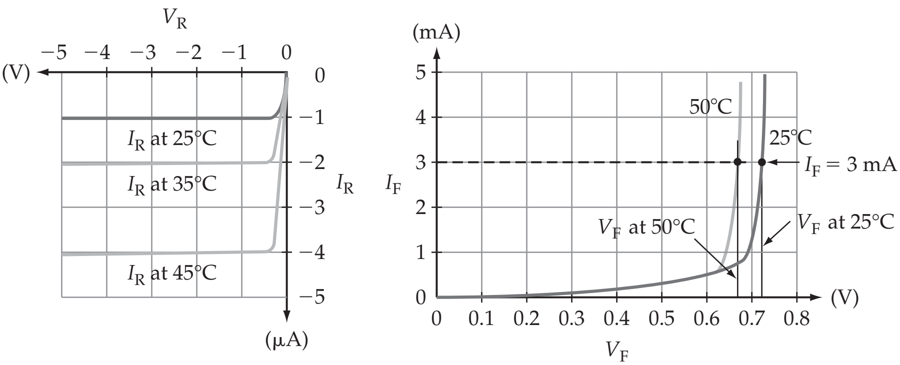
Determine the levels of reverse saturation current at temperatures of 35°C and 45°C for a junction which has I_o = 30 nA at 25°C.

Solution

Eq. 1-12: $$I_{o(T2)} \approx I_{o(T1)} (2^{T2 - T1/10})$$

At 35°C: $$I_{o(35°C)} \approx 30 \text{ nA} \times (2^{(35 - 25)/10}) \approx 60 \text{ nA}$$

At 45°C: $$I_{o(45°C)} \approx 30 \text{ nA} \times (2^{(45 - 25)/10}) \approx 120 \text{ nA}$$



(a) Reverse current approximately doubles with each 10°C temperature increase

(b) Forward voltage-drop changes by approximately −2 mV/°C

Figure 1-27 Junction reverse current and forward voltage drop are affected by temperature change.

The junction forward voltage drop (V_F) is also affected by temperature. The horizontal line (at 3 mA) on Fig. 1-27b shows that, if I_F is held constant while the junction temperature is changing, the forward voltage decreases with rising junction temperature. This means that V_F has a negative temperature coefficient. It is found that the temperature coefficient for the forward voltage of a *pn*-junction is approximately −1.8 mV/°C for a silicon junction and −2.02 mV/°C for germanium. A figure of −2 mV/°C is normally used as an approximation.

Summary

- A *pn*-junction is reverse-biased when a voltage is applied positive to the *n*-side and negative to the *p*-side.

- A reverse-biased junction has a wide depletion region.
- A very small *minority charge carrier* current (I_R) flows across a reverse-biased junction.
- The junction reverse characteristic is the graph of I_o versus V_R.
- The *reverse saturation current* (I_o) tends to be constant regardless of the reverse bias voltage (V_R).
- The reverse current approximately doubles with every 10°C rise in junction temperature.
- A *pn*-junction is *forward-biased* when a voltage is applied positive to the *p*-side and negative to the *n*-side.
- A forward-biased junction has a narrow depletion region.
- A *majority charge carrier* current (I_F) flows across a forward-biased junction.
- The junction forward characteristic is the graph of I_F versus V_F.
- The *forward current* (I_F) depends on the level of forward bias voltage (V_F).
- Typical junction forward voltage drops are 0.3 V for germanium and 0.7 V for silicon.
- The junction forward voltage drop changes by approximately −2 mV/°C as the junction temperature increases.

Section 1-7 Review

1-7.1 Sketch typical voltage/current characteristics for a forward-biased silicon *pn*-junction. Briefly explain.

1-7.2 Sketch typical voltage/current characteristics for a reverse-biased *pn*-junction. Briefly explain.

1-7.3 Discuss the effects of temperature change on forward- and reverse-biased *pn*-junctions.

Practice Problem

1-7.1 The reverse current for a semiconductor diode is measured as 25 nA at 25°C, and as 75 nA at a temperature T_2. Calculate T_2.

1-8 JUNCTION CURRENTS AND VOLTAGES

Shockley Equation

The equation relating *pn*-junction current and voltage levels is called the *Shockley equation*.

$$I_D = I_o\,[e^{V_D/nV_T} - 1] \qquad \textbf{(1-13)}$$

where I_D is the junction current, I_o is the reverse saturation current (see Section 1-7), V_D is the junction voltage, and n is a constant which is usually taken as 1 for germanium and 2 for silicon. V_T depends upon temperature

$$V_T = kT/q \tag{1-14}$$

where k is *Boltzman's constant* (1.38×10^{-23}), T is absolute temperature, and q is the electronic charge (1.6×10^{-19}). When $T = 300$ K (or 27°C), Eq. 1-14 gives

$$V_T = 26 \text{ mV}$$

Junction Current

The current level at a forward-biased junction can be calculated from Eq. 1-13 for a given applied voltage and temperature. A table of corresponding current and voltage levels could be determined for plotting the junction forward characteristic. However, the characteristics will not be completely accurate because the Shockley equation does not allow for the resistance of the semiconductor material, and for the surface leakage current that adds to the reverse saturation current. At a reverse-biased junction, the current always equals the reverse saturation current.

Example 1-5

A silicon *pn*-junction has a reverse saturation current of $I_o = 30$ nA at a temperature of 300 K. Calculate the junction current when the applied voltage is (a) 0.7 V forward bias, (b) 10 V reverse bias.

Solution

(a) Forward bias

$$V_D/(n\ V_T) = 0.7 \text{ V}/(2 \times 26 \text{ mV})$$

$$= 13.46$$

Eq. 1-13: $$I_D = I_o\,[e^{V_D/nV_T} - 1] = 30 \text{ nA}\,[e^{13.46} - 1]$$

$$= 21 \text{ mA}$$

(b) Reverse bias

$$V_D/(nV_T) = -10 \text{ V}/(2 \times 26 \text{ mV})$$
$$= -192$$

Eq. 1-13: $$I_D = 30 \text{ nA}\,[e^{-192} - 1]$$

$$= -30 \text{ nA}$$

Junction Voltage

Equation 1-13 can be rewritten to give an equation for the junction voltage for a given forward current. Here again it should be remembered that the equation is not completely accurate.

$$V_D = (n\ V_T) \ln (I_D/I_o) \tag{1-15}$$

Example 1-6

For the silicon *pn*-junction in Ex. 1-5, calculate the junction forward-bias voltage required to produce a current of (a) 0.1 mA, (b) 10 mA.

Solution

(a) $I_D = 0.1$ mA

Eq. 1-15: $V_D = (n\ V_T) \ln (I_D/I_o)$

$= 2 \times 26\ \text{mV} \times \ln (0.1\ \text{mA}/30\ \text{nA})$

$= 422$ mV

(b) $I_D = 10$ mA

Eq. 1-15: $V_D = (n\ V_T) \ln (I_D/I_o)$

$= 2 \times 26\ \text{mV} \times \ln (10\ \text{mA}/30\ \text{nA})$

$= 661$ mV

Practice Problems

1-8.1 A silicon *pn*-junction has a reverse saturation current of 20 nA at 25°C and 80 nA at 45°C. Calculate the current at both temperatures when the forward bias voltage is 0.69 V.

1-8.2 Calculate the reverse saturation current for a silicon *pn*-junction which passes a current of 15 mA at 27°C when the forward bias voltage is 680 mV.

Review Questions

Section 1-1

1-1 Describe the atom, and draw a two-dimensional diagram to illustrate your description. Compare the atom to a planet with orbiting satellites.

1-2 Define nucleus, electron, electronic charge, proton, neutron, shell, positive ion, and negative ion.

1-3 Sketch two-dimensional diagrams of silicon and germanium atoms. Describe the valence shell of each atom.

1-4 Explain atomic number and atomic weight. State the atomic number and atomic weight for silicon.

1-5 Explain what is meant by energy levels and energy bands. Sketch an energy band diagram, and define conduction band, valence band, and forbidden gap.

Section 1-2

1-6 Draw a sketch to show the process of current flow by electron motion. Briefly explain.

1-7 Draw sketches to show the process of current flow by hole transfer. Which have greater mobility, electrons or holes? Explain why.

1-8 Define conventional current direction and direction of electron flow. State why each is important.

Section 1-3

1-9 Name the three kinds of bonds that hold atoms together in a solid. What kind of bonding might be found in (a) conductors, (b) insulators, and (c) semiconductors?

1-10 Draw sketches to illustrate metallic bonding and ionic bonding. Explain what happens in each case.

1-11 Draw a sketch to illustrate covalent bonding. Explain the bonding process.

1-12 Draw energy band diagrams for conductors, insulators, and semiconductors. Explain the reasons for the differences between the diagrams.

Section 1-4

1-13 Define acceptor doping, and draw a sketch to illustrate the process. Explain.

1-14 Define donor doping, and draw a sketch to illustrate the process. Explain.

1-15 State the names given to acceptor-doped material and donor-doped material. Explain.

1-16 What is meant by majority charge carriers and minority charge carriers? Which are majority carriers and why in (a) donor-doped material, and (b) acceptor-doped material?

1-17 Explain what happens to resistance with increasing temperature in the case of (a) a conductor, (b) a semiconductor, and (c) a heavily doped semiconductor. What do you think would happen to the resistance of an insulator with increasing temperature? Why?

1-18 Explain hole-electron pair generation and recombination.

1-19 Discuss the effects that light can produce on semiconductor materials.

1-20 Define *n*-type material, *p*-type material, majority charge carriers, minority charge carriers, positive temperature coefficient, negative temperature coefficient, and dark resistance.

1-21 Discuss the relationship between the density of holes and electrons in doped and undoped semiconductor material.

Section 1-5

1-22 Draw a diagram to illustrate drift current in a semiconductor material. Briefly explain.

1-23 Draw a diagram to illustrate diffusion current in a semiconductor material. Briefly explain.

1-24 Define resistivity and conductivity.

Section 1-6

1-25 Using illustrations, explain how the depletion region and barrier voltage are produced at a *pn*-junction. List the characteristics of the depletion region.

1-26 Draw a sketch to show the depletion region and barrier voltage at a *pn*-junction with unequal doping of each side. Briefly explain.

Section 1-7

1-27 A bias is applied to a *pn*-junction, positive to the *p*-side, negative to the *n*-side. Show, by a series of sketches, the effect of this bias on depletion region width, barrier voltage, minority carriers, and majority carriers. Briefly explain the effect in each case.

1-28 Repeat Question 1-27 for a bias applied negative to the *p*-side and positive to the *n*-side.

1-29 Sketch the voltage/current characteristics for a *pn*-junction (a) with forward bias and (b) with reverse bias. Show how temperature change affects the characteristics.

1-30 State typical values of barrier voltage for silicon and germanium junctions. Discuss the resistances of forward-biased and reverse-biased *pn*-junctions.

1-31 State typical reverse saturation current levels for *pn*-junctions. Explain the origin of reverse saturation current.

Section 1-8

1-32 Write the Shockley equation for junction current in terms of junction voltage and other quantities. Define each quantity in the equation.

1-33 From the Shockley equation for junction current (for Question 1-32), derive the junction voltage equation.

Problems

Section 1-4

1-1 Determine the density of free electrons in silicon when doped with 0.6×10^{15} donor atoms/cm^3 and 10^{15} acceptor atoms/cm^3.

1-2 Repeat Problem 1-1 for germanium.

1-3 A sample of silicon is doped with 3×10^{15} acceptor atoms/cm^3 and 4×10^{15} donor atoms/cm^3. Determine the density of free electrons and holes in the sample.

1-4 A silicon sample is to have a free electron density of 5×10^{15} per cm^3 and a much smaller hole density. Calculate the required doping density for electrons if the material is already doped with 10^{15} acceptor atoms per cm^3.

Section 1-5

1-5 The drift current velocity in a germanium sample is estimated as 12.9 cm/s, and the terminal voltage is 14.5 V. Calculate the length of the sample.

1-6 Determine the conductivity and resistance of a 3 mm cube of germanium, (a) when it is purely intrinsic, and (b) when it has a hole density of $p = 5 \times 10^{14}/\text{cm}^3$.

1-7 A sample of n-type silicon is 1.5 mm long with a cross-sectional area of 0.02 mm^2. Determine the free electron density if its resistance is measured as 28 kΩ.

1-8 Calculate the resistance of a 5 mm cube of silicon described in Problem 1-1.

1-9 Determine the resistivity of the silicon described in Problem 1-3.

Section 1-7

1-10 The reverse saturation current (I_o) for a pn-junction is 25 nA at 25°C. Calculate I_o at temperatures of 30°C, 33°C, and 37°C.

1-11 The level of I_o for a pn-junction is measured as 60 nA at 30°C. Calculate I_o at 25°C.

1-12 A pn-junction has I_o = 35 nA at 25°C. Determine the junction temperature that will produce I_o = 55 nA.

Section 1-8

1-13 A forward-biased silicon junction has its current held constant at 33 mA. Calculate the junction voltage at 25°C and 50°C if the reverse saturation current is 50 nA at 25°C.

1-14 Calculate the forward current for a silicon pn-junction which has 0.65 V forward bias. The reverse saturation current is 100 nA at 25°C.

1-15 Determine the voltage change required to double the forward current for the junction in Problem 1-14.

1-16 Repeat Problem 1-14 for a silicon junction with 0.29 V forward bias.

Practice Problem Answers

1-4.1 0.7×10^{14}, 3.2×10^{6}

1-4.2 3.93×10^{13}, 1.59×10^{13}

1-5.1 1.2×10^{14}

1-5.2 0.47 V

1-5.3 44.6 Ω.cm

1-7.1 40.85°C

1-8.1 13.2 mA, 23.7 mA

1-8.2 31 nA